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CHEMICAL COMPOSITION AS A CRITERION IN IDENTIFYING METAMORPHOSED SEDIMENTS¹

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In the literature dealing with metamorphism there is repeated reference to the applicability of chemical analyses in the differentiation of schists and gneisses of sedimentary origin from those of igneous origin, and the usefulness of this method has been generally recognized. There are, however, remarkably few definite statements in regard to the exact character or magnitude of the chemical differences to be expected in rocks of these diverse origins. The compilations of Washington have within recent years made available to the geologist practically all of the superior analyses of igneous rocks published prior to 1903, and the present study was attempted in the belief that these tables furnished a basis for statistical comparisons which would lead to more definite conceptions concerning the chemical differences between igneous and meta-sedimentary rocks. In making these comparisons the writer had to make his own compilations of analyses of the meta-sedimentary rocks, and while the results are believed to be sufficiently accurate for the purposes of this paper, a general compilation of analyses of sedimentary and meta-sedimentary rocks is highly desirable and would prove of immense service to geologists in general and to students of metamorphism in particular.

The literature of this subject is not extensive and may be summarized as follows:

The subject has been treated more fully by Rosenbusch² than by any other writer. He points out³ that the proportions of the con-

¹ Published with the permission of the Director of the United States Geological Survey.

² H. Rosenbusch, "Zur Auffassung der chemischen Natur des Grundgebirges," *Tschermak's Mineralogische und Petrographische Mittheilungen*, Neue Folge, Band XII, 1891.

³ *Ibid.*, p. 51: ". . . die Bestandtheile eines Eruptivmagmas und also eines Eruptivgesteines nicht anders als gesetzmässig sein können, während in einem mechanischen Gemenge—and das sind doch die ursprünglichen Sedimente—an und für sich eine Gesetzmässigkeit in den relativen Mengen der Bestandtheile nicht vorhanden sein muss."

stituents in an eruptive magma and also in an eruptive rock are governed by definite laws, whereas in mechanical mixtures such as the sedimentary rocks, no such definite relationships need exist. Further he says,¹ that if we find in a crystalline schist such proportions between the chemical constituents as exist in no eruptive rock, we may conclude that the same cannot have been formed from an eruptive rock through any sort of dynamic metamorphism. If on the contrary the chemical makeup of a crystalline schist is the same as that of a certain eruptive rock, we must concede that the former *may* have been formed through dynamic metamorphism from the latter, not, however, that it *must* have been so formed, since certain clay schists can unquestionably possess the composition of granites.

He further expresses the opinion that dynamic metamorphism does not greatly alter the chemical character of the rocks concerned,² and in support of this view cites (1) the close chemical resemblance of certain types among the unaltered rocks to certain of the dynamically metamorphosed rocks; of diorite schists to diorites; of certain amphibole schists to gabbros, etc.; (2) the variety of very distinct rock types found in a regionally metamorphosed province and the usual sharp demarkation between them, gradation zones (*Mischungszonen*) being for the most part absent.

He points out³ that certain gneisses are differentiated from igneous rocks by their high alumina content, the alumina being much in excess of the 1:1 ratio in which it is commonly combined with the CaO, K₂O, and Na₂O of the rock. Other gneisses though low in alumina reveal their sedimentary origin in an iron content notably higher than that of any igneous rocks carrying similar percentages of lime, magnesia, and alkalies.

Grubenmann in *Die kristallinen Schiefer*⁴ remarks as follows:

Sedimentary rocks in their chemical makeup plainly lack certain regular relationships which within certain limits are so characteristic of igneous rocks. This condition is not destroyed in the metamorphism to a crystalline schist but

¹ *Op. cit.*, pp. 51, 52.

² *Ibid.*, p. 52: "die Dynamometamorphose den chemischen Charakter der ihr unterliegenden Gesteine nicht wesentlich ändert."

³ *Ibid.*, pp. 54, 55.

⁴ Vol. I, p. 12 (translation by the writer).

becomes even more clearly defined and hence can be disclosed by the chemical analysis. Yet even this (chemical) method does not always give us the desired result, since there are rocks, such as arkoses, shaly sandstones, and sandy shales, which approach igneous rocks very closely in their chemical composition.

In his chapter on the recognition of schists of igneous origin, he adds:¹

. . . as already mentioned, the chemical makeup of igneous rocks shows certain characteristic features in the proportions in which the constituent oxides are mixed. . . . Moreover these features persist throughout the metamorphism so that the chemical analysis furnishes a second and usually a safer means of recognizing the igneous origin of a schist.

Van Hise in his *Treatise on Metamorphism*² says:

A third criterion of great importance in the discrimination of metamorphosed sedimentary and igneous rocks is chemical composition. It has been shown that the materials for sedimentary rocks are sorted, that in general there is depletion in certain of the elements as compared with the igneous rocks, and that the proportions of the elements in the sedimentary rocks are therefore different from those in the igneous rocks. Furthermore, it has been shown that in the zone of anamorphism the chemical composition of rocks is not greatly changed during the process of metamorphism, and it has already been seen that this is the only zone in which metamorphism is likely to result in the confusion of the two classes of rocks. Therefore the metamorphosed sedimentary and igneous rocks which are likely to be confused have the compositions which are characteristic of their class: the metamorphosed sedimentary rocks, with minor modifications, have the chemical composition of muds, grits, sandstones, etc.; the metamorphosed igneous rocks have the compositions of granites, diorites, etc. For both sedimentary and igneous rocks there are wide variations in chemical composition, but in general the proportions of the elements are markedly different, in the two classes, as may be seen by comparison of the composition of the metamorphosed sedimentary rocks and that of the metamorphosed igneous rocks. The criterion has great value in some cases where the criterion of banding fails, for instance, in discriminating between metamorphosed sedimentary rocks and metamorphosed tuffs. The metamorphosed sediments have their characteristic compositions, while the metamorphosed tuffs, notwithstanding the fact that they may show banding, and thus closely resemble metamorphosed sediments, have the composition of igneous rocks.

In discussing the composition of muds, he says:³

. . . muds are likely to be deficient in the more readily soluble compounds. Of these the alkalis stand first, and of the alkalis sodium is more largely dissolved,

¹ *Ibid.*, p. 13.

² Monograph XLVII, U. S. Geol. Survey, pp. 914, 915.

³ *Ibid.*, p. 889.

since a large proportion of sodium in the original igneous rocks occurs in minerals which are more readily decomposed than the minerals which bear potassium—that is, sodium occurs largely in the nephelites, sodalites, and basic feldspars, which are readily soluble; whereas the great sources of potassium are orthoclase and microcline, difficultly decomposable minerals. The materials are also apt to be depleted in calcium and magnesium, since the alkaline earths are so readily soluble. The depletion in calcium usually has gone farther than the depletion in magnesium, since in the belt of weathering much of the magnesia is retained in the serpentines and talcs. The material may or may not be depleted in iron. While aluminum and silica also have been dissolved in the belt of weathering, the solution of these substances is less rapid than of the others, and thus there is usually an increase in the relative amounts of these elements.

In discussing the analysis of a slate from the Menominee district, Mr. J. Morgan Clements says:¹

That which is most striking about the analysis is the relative proportion of the alkaline earths, lime and magnesia, the latter being present in the greater quantity. As a rule, in all of the igneous rocks (and to the igneous rocks all clay slates owe their ultimate origin), except in the non-feldspathic ultrabasic ones, the reverse condition exists, namely, the magnesia is subordinate in quantity to the lime.

Dr. F. D. Adams² remarks as follows:

When any granite or granitic rock is for long periods exposed to a process of gradual decay there finally results a mass of kaolin, often mixed with more or less chloritic material, holding the quartz of the original rocks as grains scattered thickly through it. When sorted by the action of moving water it gives rise to beds of sand and clay. The chemical processes at work during this process of decay consist in the more or less complete removal of the alkalies of the feldspar, and of the decomposition of the iron-magnesia constituents with the loss of a large proportion of the lime as compared with the magnesia.

On comparing the analyses of a series of granites and those of a series of slates, as for instance those given in Roth's *Gesteins Analysen*, the latter are seen to be on an average considerably higher in aluminum and much lower in alkalies, while at the same time they are lower in silica which has been separated both as sand and in combination with the alkalies which have gone into solution, and in most cases contain more magnesia than lime instead of more lime than magnesia as is usual in the granites.

The characteristics of foliated rocks of sedimentary origin which have been considered useful in distinguishing them from foliated rocks of igneous origin may be summarized as follows:

¹ Monograph XXXVI, U. S. Geol. Survey, pp. 59, 60.

² F. D. Adams, "Contributions to Our Knowledge of the Laurentian," *Amer. Jour. Sci.*, 3d series, Vol. L, pp. 64, 65.

I. The presence of silica in certain schists and gneisses in larger proportions than in most igneous rocks.

II. The presence in many of alumina in amounts considerably in excess of that necessary to satisfy the ratio of 1:1 in which it is combined with lime and the alkalis in the common rock-forming silicates.

III. Dominance of magnesia over lime.

IV. Dominance of potash over soda.

In the following pages the writer purposes to show that foliated structures may be developed in many rocks without important changes in chemical composition, and proposes to consider in detail the value of each of the above criteria. Before discussing the criteria further it will be well to differentiate the types of foliated rocks and determine to which ones they can be appropriately applied. The foliated rocks may be classified as follows:

FOLIATES¹

I. *Primary foliates* (flow-foliated or ortho-foliated).—Here belong the flow-gneisses and all igneous rocks whose foliated structure is original and is due to differential movements in the igneous magma before complete solidification.

II. *Secondary foliates* (metamorphic-foliated or para-foliated).—Rocks whose foliated structure has been induced by metamorphism subsequent to their complete consolidation.

1) *Meta-igneous foliates*:

- a) Meta-plutonic foliates.
- b) Meta-volcanic foliates.

2) *Meta-sedimentary foliates*:

a) Siliceous foliates.

Quartzitic schists and other metamorphic derivatives of highly quartzose sediments.

b) Calcareous foliates.

Banded marbles and other metamorphic derivatives of highly calcareous sediments.

c) Pelitic foliates.

Slates, phyllites, argillaceous schists, and other metamorphic derivatives of argillaceous sediments.

¹ The term "foliates" is here used as a convenient comprehensive term to include all rocks showing foliated structures other than bedding planes. Its use in a discussion of this kind saves frequent repetitions of the two terms, schists and gneisses, and avoids any postulate as to the primary or secondary character of the foliated structure.

d) Frangitic¹ foliates.

Arkose-schists, graywacke-schists, and other metamorphic derivatives of sediments produced by disintegration of igneous rocks without much decomposition or mechanical sorting of the constituents.

III. *Foliated in which the parallel structure is in part primary and in part secondary.*1) *Injection foliates:*

Here belong the injection gneisses.

The primary foliates whose foliated structure is due to differential movements within an igneous magma before complete solidification have the composition of massive igneous rocks and may therefore be excluded from this discussion. The foliates of the third class, typified by the injection gneisses, are also excluded for obvious reasons. The secondary foliates are therefore the only ones whose chemical characters we need discuss. The igneous and sedimentary types will be considered in order.

THE META-IGNEOUS FOLIATES

The study of chemical characteristics by the method of averaging a large number of analyses, adopted for the meta-sedimentary foliates, is not applicable to the meta-igneous group because of the great variety of rocks represented and the relative scarcity of analytical data. It is necessary to restrict ourselves to the consideration of what appear to be representative cases and to comparisons between closely related rock groups.

In Dr. Watson's admirable report on *The Granites and Gneisses of Georgia*² he gives a large number of analyses of the normal granites and the metamorphic granite-gneisses of the state. Many of the gneisses are highly contorted and thin-banded, and under the microscope show evidence of dynamic metamorphism in the presence of undulatory extinction, peripheral granulation of the mineral grains, fractures traversing the larger grains of quartz and feldspar, and frequent partial or complete recrystallization. Mineralogically they

¹ The term "frangite" (from the Latin *frango*, "to break up") and its adjective "frangitic" is proposed as a comprehensive term for all sedimentary rocks formed from the disintegration of igneous rocks without extensive decomposition or mechanical sorting. It includes unconsolidated as well as cemented and dynamically metamorphosed representatives. It includes arkoses, graywackes, grits, graywacke-schists, and gneisses, etc.

² Thos. L. Watson, *Bull. 9-A*, Geological Survey of Georgia.

are almost identical with the normal granites. To quote Dr. Watson:¹

. . . the granite-gneisses differ from the more massive rock phases (granite) simply in the marked banded or foliated structure. These are secondary structures induced by long-continued and profound dynamo-metamorphism, acting on an originally massive rock, similar, in mineralogical and chemical compositions, to the existing massive granitic areas studied. . . . The granite-gneisses represent unquestionable foliated phases of the massive granite similar to the present areas but of an earlier intrusion.

The granite-gneisses are entirely free from staurolite, andalusite, cordierite, kyanite, and similar minerals so characteristic of meta-sedimentary foliates.

In order to compare the metamorphosed and unmetamorphosed granitic rocks, the writer computed their position in the quantitative system of classification.² The granites were so similar in composition that their analyses were averaged and only the systematic position of the average computed. The results may be tabulated as follows:

GRANITES AND GRANITE-GNEISSES OF GEORGIA

| | | Class | Sub-Class | Order | Rang | Sub-Rang | Name |
|------------------------|---------------------------------|-------|-----------|-------|------|----------|---------------------------------|
| Normal granites | Average of 21 analyses | I | I | 4 | 2 | 3 | Toscanose |
| Porphyritic granites | Average of 10 analyses | I | I | 4 | 2 | 3 | Toscanose |
| | 4 analyses, separately computed | I | I | 4 | 2 | 3 | Toscanose |
| Biotite-granite gneiss | 2 analyses, separately computed | I | I | 4 | 2 | 3-4 | Between Toscanose and Lassenose |
| | 3 analyses, separately computed | I | I | 4 | 1 | 3 | Liparose |

It will be seen therefore that the granite-gneisses possess the composition of igneous rocks and are almost identical with the normal

¹ *Ibid.*, p. 263.

² Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks*, 1903.

granites in composition. In Washington's tables¹ there are 141 representatives of the sub-rang Toscanose, 85 of Lassenose, and 103 of Liparose. They are mainly granites, rhyolites, and related rocks.

If we examine the individual analyses in respect to the proportions between MgO and CaO and between K₂O and Na₂O, we find added evidence of similarity.

| | MgO > CaO | K ₂ O > Na ₂ O |
|---|----------------------|--------------------------------------|
| In the normal and porphyritic granites..... | 0 out of 39 analyses | 22 out of 35 analyses |
| In the granite-gneisses..... | 0 out of 10 analyses | 7 out of 10 analyses |

The granite-gneisses of this region therefore possess all the chemical characteristics of certain very common types of igneous rocks.

A large number of granites and granite-gneisses of Sweden have been described by Holmquist² in his "Studien über die Granite von Schweden." Many of these have been affected by dynamic metamorphism and show strongly developed parallel structure. Under the microscope they either exhibit well-defined kataclastic structure

METAMORPHOSED GRANITES OF SWEDEN

| No. of Analyses | Holmquist's Numbers | Class | Sub-Class | Order | Rang | Sub-Rang | Name | Number of Representatives in Washington's Tables |
|-----------------|------------------------|-------|-----------|-------|------|----------|---------------|--|
| 2..... | 103, 116 | I | I | 3 | 2 | 3 | Tehamose | 39 |
| 4..... | 21, 120, 123, 134 | I | I | 4 | 1 | 3 | Liparose | 103 |
| 5..... | 97, 117, 121, 122, 131 | I | I | 4 | 2 | 3 | Toscanose | 141 |
| 3..... | 19, 20, 104 | I | I | 4 | 2 | 4 | Lassenose | 85 |
| 3..... | 127, 135, 136 | I | I | 4 | 3 | 3 | Amiatose | 23 |
| 1..... | 137 | I | I | 4 | 3 | 4 | Yellowstonose | 62 |
| 2..... | 100, 124 | II | I | 4 | 2 | 3 | Adamellose | 25 |
| 1..... | 25 | II | I | 4 | 2 | 4 | Dacose | 26 |
| 1..... | 130 | II | I | 4 | 3 | 3 | Harzose | 31 |
| 1..... | 22 | II | I | 4 | 3 | 4 | Tonalose | 124 |
| 3..... | 101-125, 126 | II | I | 5 | 2 | 4 | Akerose | 44 |
| 1..... | 102..... | II | I | 5 | 3 | 4 | Andose | 128 |

¹ H. S. Washington, "Chemical Analysis of Igneous Rocks," *Professional Papers Nos. 14 and 28*, U. S. Geol. Survey, 1903 and 1904.

² Holmquist, *Bull. Geol. Institution*, University of Upsala, Vol. VII, pp. 77-269 (1904-5).

or else have suffered complete recrystallization. The position in the quantitative system of 27 of these metamorphosed granitic rocks was computed, and they were found without exception to fall in sub-rangs represented by numerous examples among massive igneous rocks. Their classification is as appears in the preceding table.

A comparison of the magnesia-lime ratios and alkali ratio in these granite-gneisses with those in the granites gave the following results:

| | MgO > CaO | K ₂ O > Na ₂ O |
|------------------------------------|-----------------------|--------------------------------------|
| In the unmetamorphosed granites... | 1 out of 105 analyses | 82 out of 105 analyses |
| In the metamorphosed granites..... | 1 out of 27 analyses | 14 out of 27 analyses |

None of the metamorphosed granites show alumina in excess of the amounts common in many massive igneous rocks. Corundum is present in the norm of 8 out of the 27 metamorphosed rocks, but is never in excess of 2 per cent. From their chemical composition alone, therefore, it would be impossible to distinguish these 27 rocks from typical massive igneous varieties.

Certain rocks described by Teall¹ as early as 1885 afford an example of the dynamic metamorphism of a basic rock without notable changes in chemical composition. Two basic dikes traversing the more acid gneisses of Sutherlandshire, Scotland, are in part massive and in part highly schistose, the schistose portions being so distributed as to show that they were not produced by flowing movements in the dike before complete solidification, but are the result of regional metamorphism. Upon microscopic examination the massive phase is found to have the mineral composition and ophitic texture of a typical diabase, while the schistose phase is a hornblende schist devoid of kataclastic structures but with a perfect parallel structure, which is plainly the result of complete recrystallization. The principal mineral changes accompanying the development of the schistose structure are the replacement of augite by hornblende and the appearance of some free quartz in the schist. The chemical composition of the two rocks, as shown in analyses I and II, p. 454, is almost identical.

¹ J. J. H. Teall, *Quart. Jour. Geol. Soc.*, London, Vol. XLI, pp. 133-45 (1885).

| | I DIABASE | | II HORNBLÉNDÉ SCHIST | |
|--------------------------------------|--------------|------------|-------------------------|------------|
| | Per cent. | Mol. Prop. | Per cent. | Mol. Prop. |
| SiO ₂ | 47.45 | .791 | 49.78 | .830 |
| Al ₂ O ₃ | 14.83 | .145 | 13.13 | .128 |
| Fe ₂ O ₃ | 2.47 | .016 | 4.35 | .027 |
| FeO..... | 14.71 | .204 | 11.71 | .163 |
| MgO..... | 5.00 | .125 | 5.40 | .135 |
| CaO..... | 8.87 | .158 | 8.92 | .159 |
| Na ₂ O..... | 2.97 | .048 | 2.39 | .039 |
| K ₂ O..... | 0.99 | .011 | 1.05 | .011 |
| H ₂ O..... | 1.00 | .... | 1.14 | .... |
| TiO ₂ | 1.47 | .019 | 2.22 | .028 |
| CO ₂ | 0.36 | .... | 0.10 | .... |
| MnO..... | .... | .... | 0.27 | .004 |
| Totals..... | 100.12 | .... | 100.46 | .... |

| Norm of I | | | Norm of II | |
|-----------|-------|---|---|-------------|
| Salic | 55.18 | $\left\{ \begin{array}{l} 6.12 \\ 25.15 \\ 23.91 \end{array} \right.$ | $\left\{ \begin{array}{l} 2.76 \\ 6.12 \\ 20.44 \\ 21.68 \end{array} \right.$ | 51.00 Salic |
| Femic | 43.69 | $\left\{ \begin{array}{l} 2.89 \\ 3.71 \\ 16.89 \\ 2.38 \\ 17.82 \end{array} \right.$ | $\left\{ \begin{array}{l} 4.26 \\ 6.26 \\ 18.68 \\ 19.00 \end{array} \right.$ | 48.20 Femic |
| | | Ilmenite Magnetite Diopside Hypersthene Olivine | | |

Both rocks fall in class III, order 5, rang 3, and sub-rang 4, Camptonose.¹

It will be seen therefore that, in spite of complete recrystallization, of complete change in texture, and of notable change in mineral composition, the chemical makeup of the rock has suffered little change.

A few other examples similar to those cited above are available in geologic literature and might be quoted if space permitted. The mass of chemical data, however, bearing on the metamorphism of igneous rock is regrettably small and the field is one of the most promising for geologic investigation.

In the opinion of the writer the data cited above show that in many cases perfect parallel structures have been developed in igneous

¹ Two changes are worthy of note in passing: first, the appearance of quartz both in the norm and the mode of the schist, and second, the change of some of the iron from the ferrous to the ferric state.

rocks without important changes in chemical composition. It lends support to the view expressed by Rosenbusch that most foliated rocks of igneous origin have not suffered any great chemical changes during dynamic metamorphism. It does *not* prove, however, that important chemical changes may not take place in *some* igneous rocks as a result of dynamic metamorphism.

THE META-SEDIMENTARY FOLIATES

Among the foliated rocks of meta-sedimentary origin the siliceous foliates may usually be recognized without detailed chemical studies from their highly quartzose character. Being more resistant than most other sediments to mass deformation they are also more likely to preserve during metamorphism traces of bedding and other original structures. It is seldom therefore that chemical data need be appealed to for the recognition of sediments of this type. The calcareous foliates also are usually recognized readily from their high carbonate content without recourse to refined chemical study.

It is evident, on the other hand, that the frangitic foliates, rocks like the arkose and graywacke-schists, which are the result of the disintegration of igneous rocks without much decomposition or mechanical sorting, will closely resemble their parent igneous rocks chemically, and that in such cases chemical criteria have little or no value for determining genesis. It is only in the recognition of the remaining division, the pelitic foliates, that chemical criteria are particularly useful, and it is here that they have been most frequently appealed to. It should be remembered, however, that the four types of sediments mentioned above are not sharply delimited but pass into each other through every conceivable gradation. It is not possible therefore to define the exact limits of usefulness of chemical criteria, though the major limitations outlined are believed to be essentially correct.

The chemical characteristics of the metamorphosed pelitic sediments can only be adequately studied by comparing a considerable number of analyses of slates, phyllites, and schists.

No. I below represents the average of 79 slate and phyllite analyses, 36 being from the United States and Canada and 43 from Europe. Only those of undoubted sedimentary origin and unaffected by contact

metamorphism were used. The majority are roofing slates. In the second column the averages are recomputed on the water-free basis. No. II represents the average of the analyses of 30 pelite schists and gneisses, mostly European, though a few from the United States and Canada were used. Only those definitely stated to be of sedimentary origin, or whose mineral character or geologic occurrence clearly showed that such was the case, were included. Schists affected by

I. SLATES AND PHYLLITES

| | NO. OF DETERMINATIONS | AVERAGES OF ANALYSES | | AVERAGES CORRECTED FOR TOTAL WATER | |
|--------------------------------------|-----------------------|----------------------|------------|------------------------------------|------------|
| | | Percentage Weights | Mol. Prop. | Percentage Weights | Mol. Prop. |
| SiO ₂ | 79 | 60.49 | 1.008 | 62.97 | 1.049 |
| Al ₂ O ₃ | 79 | 17.56 | 0.172 | 18.28 | 0.179 |
| Fe ₂ O ₃ | 48 | 2.74 | 0.017 | 2.85 | 0.018 |
| FeO..... | 48 | 4.61 | 0.064 | 4.79 | 0.067 |
| MgO..... | 79 | 2.51 | 0.063 | 2.61 | 0.065 |
| CaO..... | 79 | 1.26 | 0.023 | 1.31 | 0.023 |
| K ₂ O..... | 74 | 3.31 | 0.035 | 3.44 | 0.036 |
| Na ₂ O..... | 74 | 1.32 | 0.021 | 1.37 | 0.022 |
| TiO ₂ | 46 | 0.73 | 0.009 | 0.76 | 0.010 |
| CO ₂ | 35 | 1.11 | 0.025 | 1.16 | 0.026 |
| H ₂ O+..... | 28 | 3.61 | 0.201 | .... | .... |
| H ₂ O-..... | 28 | 0.31 | 0.018 | .... | .... |
| Total..... | .... | 99.56 | .... | 99.54 | .... |

II. PELITE SCHISTS AND GNEISSES

| | NO. OF DETERMINATIONS | AVERAGES OF ANALYSES | | AVERAGES CORRECTED FOR TOTAL WATER | |
|--------------------------------------|-----------------------|----------------------|------------|------------------------------------|------------|
| | | Percentage Weights | Mol. Prop. | Percentage Weights | Mol. Prop. |
| SiO ₂ | 30 | 65.46 | 1.091 | 66.67 | 1.113 |
| Al ₂ O ₃ | 29 | 16.32 | 0.160 | 16.64 | 0.163 |
| Fe ₂ O ₃ | 22 | 4.04 | 0.025 | 4.12 | 0.026 |
| FeO..... | 22 | 2.71 | 0.038 | 2.76 | 0.038 |
| MgO..... | 30 | 2.42 | 0.060 | 2.47 | 0.062 |
| CaO..... | 30 | 1.50 | 0.027 | 1.53 | 0.027 |
| K ₂ O..... | 30 | 3.40 | 0.036 | 3.47 | 0.037 |
| Na ₂ O..... | 30 | 1.89 | 0.031 | 1.93 | 0.031 |
| TiO ₂ | 24 | 0.89 | 0.011 | 0.91 | 0.011 |
| CO ₂ | .. | none | .... | .... | .... |
| H ₂ O+..... | 9 | 1.87 | 0.103 | .... | .... |
| H ₂ O-..... | 9 | 0.09 | 0.006 | .... | .... |
| Total..... | .. | 100.59 | .... | 100.59 | .... |

contact metamorphism were also ruled out as far as possible. In the supplementary column the averages are recomputed to the moisture-free basis. The close relationship between the slate and schist averages is at once apparent. A notable feature of both is the dominance of MgO over CaO and of K₂O over Na₂O. It is noteworthy

| | Sub-Class | Order | Rang | Sub-Rang | Remarks |
|--------------------|-----------|-------|------|----------|---|
| Class I. Persalane | I | 2 | 1 | 3 | 2 representatives of this sub-rang in W. T. ;* 1 is schistose and not fresh. |
| | I | 2 | 4 | 5 | No representative of this rang in W. T. |
| | I | 3 | 2 | 3 | Tahamose; 29 representatives of this sub-rang in W. T. |
| | I | 3 | 2 | 4 | Alsbachose; 17 representatives of this sub-rang in W. T. |
| | I | 3 | 3 | 2 | 8 representatives of this sub-rang in W. T. |
| | I | 3 | 3 | 4 | 6 representatives of this sub-rang in W. T. |
| | I | 3 | 4 | 2 | 2 representatives of this rang and 1 of this sub-rang in W. T. |
| | I | 3 | 4 | 4 | No representative of this sub-rang in W. T. and only 2 of this rang. |
| | I | 3 | 4 | 4 | |
| | I | 4 | 2 | 3 | Toscanose; 122 representatives of this rang in W. T. |
| | I | 4 | 2 | 3 | Only 5 representatives of this sub-class and 1 of this sub-rang in W. T. |
| | II | 3 | 2 | 2 | |

* W. T.=abbreviation for Washington, "Tables of Chemical Analyses of Igneous Rocks," *Professional Paper No. 14*, U. S. Geol. Survey, 1903.

| | Sub-Class | Order | Rang | Sub-Rang | Remarks |
|--------------------|-----------|-------|------|----------|---|
| Class II. Dosalane | I | 2 | | } | No representative of this order in W. T. |
| | I | 2 | | | |
| | I | 3 | 2 | 2 | 1 representative of this sub-rang in W. T. |
| | I | 3 | 2 | 3 | 2 representatives of this sub-rang in W. T. |
| | I | 4 | 1 | 2 | No representative of this sub-rang in W. T. |
| | I | 4 | 1 | 2 | |
| | I | 4 | 2 | 3 | Adamellose; 21 representatives of this sub-rang in W. T. |
| | I | 4 | 2 | 3 | |
| | I | 4 | 2 | 3 | |
| | I | 4 | 2 | 3 | |
| | I | 4 | 2 | 3 | |
| | I | 4 | 2 | 3 | |
| | II | | | } | Only 4 representatives of this sub-class in W. T. and all these are stated to be possible products of contact metamorphism. |
| | II | | | | |
| | II | | | | |
| | II | | | | |
| | II | | | | |

also that the silica content is much higher in the schist average (65.46) than in the slate average (60.49).

The chemical characteristics of the pelitic foliates cannot, however, be fully inferred from averages, but must be based also on a consideration of individual analyses which furnish a measure of the possible extent of variation in composition. It is instructive, therefore, especially in comparing the pelites with igneous rocks, to treat them for the time being as if they *were* igneous rocks and compute their position in the quantitative system of classification. This has been done for the thirty analyses of pelite schists and gneisses used in these studies, for their average, and for the average of the 79 slate and phyllite analyses. The results are as tabulated in the preceding tables.

The average of the 30 schist analyses falls in class II, sub-class I, order 3, rang 2, sub-rang 3, while that of the 79 slate analyses falls in class II, sub-class I, order 3, rang 4, and sub-rang 2 to 3.

We see from the above table, therefore, that the calculation of the position of these pelitic foliates in the quantitative system serves at once to reveal marked differences between some of them and any known igneous rocks. Others, however, fall in divisions characterized by numerous igneous representatives.

COMPARISON OF COMPOSITION OF IGNEOUS AND SEDIMENTARY FOLIATES

With these preliminary and partial studies of the chemical characteristics of igneous and sedimentary foliates we may proceed to a more minute comparison of the two types with especial reference to the criteria which have been applied by various geologists in distinguishing them. Before taking up the detailed comparisons it may be well, however, to state as clearly as possible the general premises upon which the comparisons are based. These are three in number:

First, Among the meta-sedimentary foliates only the pelites need enter into the comparison. This premise has already been fully considered and will hardly be questioned.

Second, The distinctive chemical characters of the pelites have been developed, not during dynamic metamorphism, but earlier, in the belt of weathering. Most metamorphosed igneous rocks having

never been in the belt of weathering have not been affected by the same kinds of chemical changes.

Third, Both pelites and igneous rocks undergo chemical changes during dynamic metamorphism, but in many if not in most cases, these are not of sufficient magnitude to obscure the original igneous or sedimentary characters. The nature and value of various chemical criteria may therefore be determined by a direct comparison of the pelites with the unaltered igneous rocks as tabulated in Washington's tables. The changes that do take place in igneous rocks during metamorphism appear to be of lesser magnitude and of a different character from those which affect the sediments. Professor C. K. Leith in a letter to the writer has formulated the conception that under conditions of anamorphism, both igneous and sedimentary rocks tend toward a common rock type characterized by a few platy and columnar minerals such as mica, chlorite, talc, hornblende, etc., and that constituents in excess of the proportions necessary to the formation of these minerals will be driven off. To the writer's mind this also involves the conception of a possible *addition* of similar materials to other rocks where their presence may facilitate the development of such minerals. The conception is an interesting and valuable one. From the theoretical standpoint it is necessary to admit the possibility of profound chemical changes as a result of prolonged dynamic metamorphism, and it seems indeed probable that certain rocks now exposed in the older terranes may have been affected by such processes. The point particularly pertinent to the present discussion is the extent to which such equalizing action has gone on among most of the metamorphic rocks with which the geologist has to deal. The evidence already cited seems to the writer to indicate that complete recrystallization with the development of perfect foliated structures *may* take place in both igneous rocks and pelitic sediments, without changes of sufficient magnitude to obscure their original sedimentary or igneous character. Changes in silica content are a possible exception.

The possibility is fully recognized, however, that in certain cases prolonged and severe dynamic metamorphism may produce changes in igneous or sedimentary rocks which render chemical differentiation between them difficult or impossible.

CRITICAL VALUE OF THE ALUMINA CONTENT

The absolute content of alumina in a rock has little critical value unless the proportion be strikingly unusual. What is of significance, however, is its proportion in relation to the bases, lime, and the alkalies, with which, in rocks, it is commonly combined. The high content of alumina in proportion to these bases in the class of pelitic sediments is too well understood to require extended discussion here. It is well known that this arises from two causes, (1) the tendency toward a concentration of alumina in the finer portions, and of silica in the coarser portions of soils and other products of rock disintegration;¹ and (2) the comparatively stable and insoluble character of alumina which leads to an increase in its relative abundance when rocks are acted upon by solutions. In the analyses of metamorphic rocks available to the writer there is no evidence that the proportion of alumina relative to lime and the alkalies varies greatly under conditions of anamorphism such as exist during the development of foliated structures. The increase on the contrary takes place under conditions of katamorphism, especially within the belt of weathering, and is frequently manifest in the development of silicates such as kaolinite, hydro-micas, etc., proportionately richer in alumina and poorer in silica and bases than the more common aluminum silicates of igneous rocks.

In the igneous rocks, lime and the alkalies are the common bases with which alumina is combined, usually in the proportions of 1:1 in the feldspars, muscovite, nephelite, etc. In most igneous rocks alumina is not present in excess of the 1:1 ratio to the available lime and alkalies. In others it exceeds this ratio but the excess is almost invariably small. If in an unweathered foliated rock the excess is large it throws doubt at once upon its igneous origin.

It is a very simple matter to determine the amount of "excess" alumina present in all the superior analyses of igneous rocks tabulated in Washington's tables, since in computing the norm of these rocks for classification according to the quantitative system, alumina is first allotted to K_2O , Na_2O , and CaO in the proportions of 1:1 and the excess of alumina calculated as corundum. The excess

¹ Literature summarized in Failyer, Smith, and Wade, "The Mineral Composition of Soil Particles," *Bull.* 54, Bureau of Soils, U. S. Dept. of Agriculture.

is therefore represented by the percentage of corundum in the norm.

Corundum is present in the norm of 501 out of the 1,892 superior analyses in Washington's tables. Of the 501, 490 belong to the more acid classes I and II.

The corundum in the norm exceeds 5 per cent. in only 52 out of the 1,892 analyses, or less than 3 per cent.

The corundum in the norm exceeds 10 per cent. in only 12 out of the 1,892 analyses, or about $\frac{3}{8}$ of 1 per cent. Of these 12 analyses, 11 fall in sub-class II of the quantitative system in which the ratio of quartz + feldspar + leucites to corundum + zircon is less than $\frac{7}{4}$. Four of the 11 members of this sub-class are stated to be possible products of contact metamorphism and 2 others are a corundum syenite and a corundum pegmatite, respectively.

Among the 30 pelitic foliates which enter into the average given in the table on p. 456 and which are classified in the table on p. 457, 19 show over 5 per cent. of corundum (excess alumina) in the norm and 9 show over 10 per cent. Six of the latter fall in the aluminous sub-class II of the quantitative system. The average of the 30 pelite schist analyses shows 7 per cent. of corundum in the norm and the average of the 79 slate analyses $9\frac{1}{2}$ per cent.

Among the pelites and meta-igneous rocks which have been considered there is no evidence that the alumina content changes materially during the development of foliated structures. It seems safe to conclude therefore:

I. *That a sedimentary origin is to be suspected when the analysis of a fresh foliate shows Al_2O_3 in excess of 5 per cent. over the 1:1 ratio necessary to satisfy the K_2O , Na_2O , and CaO present.*

II. *That when this excess exceeds 10 per cent. a sedimentary origin is extremely probable.*

CRITICAL VALUE OF THE MAGNESIA-LIME RATIO

The importance of carbonation as a phenomena of those portions of the lithosphere in which solution is active has been fully discussed by Van Hise and others. By this process much of the lime and magnesia present in the silicate minerals of igneous rocks becomes converted into the more soluble form of carbonates and suffers partial

removal in solution. The solubility of these carbonates is dependent upon a large number of factors, but in a general way calcium carbonate is more readily soluble than magnesium carbonate. In a rock, therefore, which contains both lime and magnesia, the lime is usually removed more rapidly than the magnesia and the relative amount of magnesia shows a progressive increase.

Since this selective removal of carbonates is largely effected through the agency of circulating waters it is a phenomenon more characteristic of the upper zone of the lithosphere than of the deeper zone in which secondary foliated structures are developed. There appears to be little evidence that the processes which have produced the foliated structures in most of the metamorphic rocks have effected any great changes in the relative proportions in which CaO and MgO are present in the rock, the tendency under these conditions being for these oxides to combine in the more stable form of silicates. If, for example, we compare the percentages of lime and magnesia in the composite analysis of 51 Paleozoic shales made in the laboratory of the U. S. Geological Survey¹ with the percentages shown in the table on p. 456 for the averages of the slate and pelite schist analyses, we find that the relative proportions are closely similar in the three groups. The percentage weights corrected for the water content are given below:

| | MgO | CaO |
|-------------------------------|-------|-------|
| (1) Shales | 2.43% | 1.48% |
| (2) Slates | 2.61 | 1.31 |
| (3) Schists and gneisses..... | 2.47 | 1.53 |

It appears clear from these comparisons that dominance of magnesia over lime is a feature developed in the pelitic sediments, not during dynamic metamorphism but during the processes of rock disintegration and decay.

A comparison of the pelitic foliates with the igneous rocks as tabulated in Washington's tables gives the relationships with respect to magnesia and lime shown in the first column of the table below.

Among the 79 analyses of sedimentary slates which enter into the average given in the table on p. 456, MgO > CaO in 84 per cent., while among the 30 pelite schist analyses whose average was given in the

¹ F. W. Clarke, *Bull.* 330, U. S. Geol. Survey, p. 468 (1908).

table on p. 456, this relationship holds in 77 per cent. It has already been shown (see table on p. 457) that all of the pelite schists when classified according to the quantitative system fall in the more acid classes I and II and usually near the border between these two classes. A fair comparison of the composition of the pelitic foliates and the igneous rocks should include therefore only the more acid classes I and II among the latter. Among the igneous rock of classes I and II of Washington's tables, MgO exceeds CaO in only 8 per cent., a

| | Percentage Weight of MgO > CaO | Percentage Weight of K ₂ O > Na ₂ O | Percentage Weights of Both MgO > CaO and K ₂ O > Na ₂ O |
|---|-----------------------------------|--|--|
| Slates..... | (79) 84 per cent. | (74) 92 per cent. | (74) 78 per cent. |
| Pelite schists and gneisses..... | (30) 77 per cent. | (30) 83 per cent. | (30) 74 per cent. |
| Igneous rocks of classes I and II, Washington's tables*..... | (1481) 8 per cent. | (1481) 36½ per cent. | (1481) 4½ per cent. |
| Igneous rocks of classes III, IV, and V..... | (411) 35 per cent. | (401) 14 per cent. | (401) 7 per cent. |

* H. S. Washington, "Chemical Analyses of Igneous Rocks," *Professional Paper No. 14*, U. S. Geol. Survey, 1903.

The figures in parenthesis denote the number of analyses considered in each case.

figure markedly in contrast with the 84 per cent. and 77 per cent. observed in the slates and pelite schists, respectively. For the igneous rocks of the neutral and basic types of classes III, IV, and V in Washington's tables, the number of analyses in which MgO > CaO is about 35 per cent. The *amount* of this dominance is also much greater in many of the basic rocks than in the acid.

Dominance of magnesia over lime is therefore of very considerable value as a criterion of genesis. Its value is greater in the case of acid than of basic foliates.

CRITICAL VALUE OF THE POTASH-SODA RATIO

Attention is frequently called in geological literature to the fact that sodium salts are in general more soluble than the corresponding salts of potash, as an explanation of their more rapid removal from rocks in the processes of weathering. Their rate of removal is not

so much a matter of relative solubility of corresponding salts, however, as of the particular mineral combinations in which soda and potash are most commonly present in rocks. The commonest potash minerals are muscovite and the potash feldspars, orthoclase and microcline. The commonest soda minerals, on the other hand, are the plagioclase feldspars, nephelite, sodalite, etc., which are much more readily decomposed.

The more rapid removal of soda than of potash in the processes of rock weathering is apparent from the comparisons which have been made by Merrill and others¹ of weathered rocks with the rocks from which they have been derived.

Another line of evidence is furnished by analyses of stream and underground waters of areas whose rocks are of known and uniform character. Hanamann² found in studying the stream waters of the Erz and Karlsbad mountains in Bohemia that "the tributaries from the granitic highlands are rich in silica, soda, and potash. While in the granites of Bohemia . . . the soda is to the potash as 1:2, we find that in the waters this ratio is reversed."³

The granites of Maine as shown by numerous analyses and field studies⁴ contain potash feldspar, orthoclase or microcline, as their dominant feldspar, usually with oligoclase as the subordinate feldspar. The ratio $\frac{K_2O}{Na_2O}$ varies in the available analyses from $\frac{1.3}{1}$ to $\frac{1.8}{1}$. In the ten analyses of groundwaters from the granitic rocks of the state⁵ soda dominates over potash in every case, the ratio $\frac{Na_2O}{K_2O}$ varying from $\frac{1.4}{1}$ to $\frac{17.0}{1}$. Of especial interest is an analysis of water

¹ See Geo. P. Merrill, *Rocks, Rock Weathering and Soils*, pp. 185-213 (1906); also Thomas L. Watson, "Granites and Gneisses of Georgia," *Bull. 9-A*, Geol. Survey of Georgia, pp. 298-348 (1902).

² Dr. Jos. Hanamann, "Die chemische Beschaffenheit der fliessenden Gewässers Bohmens," *Archiv der naturwissenschaftlichen Landesdurchforschung von Böhmen*, Band IX, pp. 48, 87, 88. This report discusses also the characters of waters derived from other types of rocks.

³ Translation by the writer.

⁴ See T. Nelson Dale, "The Granites of Maine," *Bull. 313*, U. S. Geol. Survey, 1907.

⁵ F. G. Clapp and W. S. Bayley, "Underground Waters of Southern Maine," *Water-Supply Paper No. 223*, U. S. Geol. Survey, p. 77 (1909).

from a well on Settlement Hill, two miles northeast of Stonington. The rock of this hill is wholly granite and it is largely bare of drift. The hill which is 120 feet high forms a peninsula connected by a low narrow neck to the main part of Deer Isle. Being thus practically surrounded by the ocean waters, its groundwaters quite certainly derive their mineral content from the granite of the hill. The analysis of water from a well 279 feet deep in the granite here is as follows:

| | Parts per Million |
|---|-------------------|
| Total solids..... | 136.0 |
| Organic and volatile matter..... | 19.0 |
| Silica (SO ₂) | 11.2 |
| Iron and aluminum oxides (Fe ₂ O ₃ +Al ₂ O ₃)..... | 2.0 |
| Calcium (Ca)..... | 29.0 |
| Magnesium (Mg)..... | 3.4 |
| Sodium (Na) | 13.0 |
| Potassium (K)..... | 1.9 |
| Sulphate radical (SO ₄)..... | 26.0 |
| Chlorine (Cl)..... | 17.0 |

The granite of this hill shows dominant potash with orthoclase-microcline as its dominant feldspar. In the solution of its constituents by the groundwaters the alkali ratio has therefore been reversed. Contamination from sea water is very improbable, not only in the nature of the case, but because of the low chlorine content. The dominance of lime over magnesia in the water is also greater than in the granite, indicating that the lime is being removed more rapidly than the magnesia.

Instances of a character similar to those cited above might be multiplied to show the general tendency for soda to be removed more rapidly than potash in the processes of rock weathering. While this is the general rule exceptions are of course numerous.

There is no evidence of important changes in the potash-soda ratio in the pelitic sediments during dynamic metamorphism and the development of foliated structures. If we compare the percentages of potash and soda in the analysis of the composite sample of 78 shales¹ made in the laboratory of the U. S. Geological Survey, with the

¹ See F. W. Clarke, "The Data of Geochemistry," *Bull.* 330, U. S. Geol. Survey, p. 468 (1908).

percentages for slates and schists given in the table on p. 456, we find, as shown below, that there is no indication of any tendency toward an increase of the $\frac{K_2O}{Na_2O}$ ratio.

| | K ₂ O | Na ₂ O |
|---------------------------------|------------------|-------------------|
| Shales..... | 3.42 per cent. | 1.38 per cent. |
| Slates and phyllites..... | 3.44 | 1.37 |
| Pelite schists and gneisses.... | 3.47 | 1.93 |

The comparisons already made between igneous and meta-igneous rocks also reveal no important changes in the potash-soda ratio during dynamic metamorphism. The process is believed therefore to go on largely under conditions of katamorphism and particularly in the belt of weathering.

If we compare the potash-soda relationships in the available analyses of slates and pelite schists with those in the igneous rocks, as was done for the lime-magnesia ratio, the results recorded in the second column of the table on p. 463 are obtained. For reasons already stated (p. 463) a fair comparison includes only classes I and II among the igneous rocks. Among the 74 slate analyses whose average is given in the table on p. 456, in which the alkalis were separately determined, $K_2O > Na_2O$ in 92 per cent., while among the 30 pelite schist analyses considered this relation holds in 83 per cent. Among the 1,481 igneous rocks of classes I and II tabulated in Washington's tables, $K_2O > Na_2O$ in $36\frac{1}{2}$ per cent., while among the 401 rocks of the more basic classes III, IV, and V, the relation holds in about 14 per cent.

The difference in the rates of removal of potash and soda during rock weathering, though less marked than in the case of lime and magnesia, are nevertheless of sufficient magnitude to be of value as a criterion of genesis. Its value is even greater in the case of basic rocks than of acid.

CRITICAL VALUE OF THE DOUBLE RELATIONSHIP $MgO > CaO$
AND $K_2O > Na_2O$

If we examine the slate and pelite schist analyses which enter into the averages of the table on p. 456, we find that there is a dominance of MgO over CaO and also of K_2O over Na_2O in 78 per cent.

of the slate analyses and 74 per cent. of the pelite schist analyses. In the igneous rocks of Washington's tables this double relationship holds in only $4\frac{1}{3}$ per cent. of the rocks of classes I and II and in 7 per cent. of the rocks of classes III, IV, and V. These relations are tabulated in the third column of the table on p. 463. The double relationship is therefore of much more diagnostic value than either of the single relationships. If we consider the pelites in comparison with the igneous rocks of classes I and II, the double relationship has about twice the critical value of dominance of only MgO over CaO, and over eight times the value of dominance of only K₂O over Na₂O.

CRITICAL VALUE OF THE SILICA CONTENT

Attention has already been called to the fact that certain types of metamorphosed sediments, such as quartzites and quartzitic schists, are usually readily identified as such from their highly quartzose character without the necessity of further chemical study. There is however every variation from such extremely siliceous types to typical pelites, and it is to be expected that in many of these intermediate types the high silica content will have diagnostic value.

It has been shown that the Al₂O₃ content, the $\frac{\text{MgO}}{\text{CaO}}$ ratio, and the $\frac{\text{K}_2\text{O}}{\text{Na}_2\text{O}}$ ratio in a rock exhibit no important change during dynamic metamorphism. The SiO₂ content, on the contrary, often increases very markedly during metamorphism. This is shown by a comparison of the average of the pelite schist analyses with the slate average in the table on p. 456. A discussion of the cause of this silication is beyond the scope of this paper. It has usually been explained as a process complementary to decarbonation, CO₂ being driven off during dynamic metamorphism and carbonates converted into silicates. Studies which the writer has in hand have led him to believe, however, that while silication as a result of decarbonation undoubtedly takes place, it is quantitatively inadequate to explain the large silica increases observed. It seems probable that there is actual addition of silica from outside, either through the agency of descending groundwaters or from magmatic sources. The comparisons of igneous with meta-igneous rocks which have been given in this paper afford slight and

inconclusive evidence of silication in metamorphism. The process is so marked, however, in the case of the pelites that it seems probable it may also assume important magnitude in the metamorphism of certain igneous rocks.

High silica content as a criterion of sedimentary *versus* igneous origin must therefore be used with more reservation than the other criteria we have considered, since it may be developed in an igneous rock during metamorphism. Used in connection with other criteria it may have very considerable confirmatory value. Used alone it is of very questionable value.

As in the case of alumina, it is not the percentage as given in the analysis that is significant, but the excess silica remaining after silica has been allotted to the bases present in the proportions in which it is usually present in the common rock-making minerals. This excess silica appears as quartz in the norm when the rock is classified according to the quantitative system.

The amounts of "excess" silica characteristic of igneous rocks may be inferred from the following comparisons of the analyses tabulated in Washington's tables:

In class I, only 25 analyses show over 50 per cent. of quartz in the norm and only 7 analyses show over 60 per cent. out of the 762 tabulated.

In class II, only 14 analyses show over 30 per cent. of quartz in the norm and only 1 analysis shows over 40 per cent. out of the 719 tabulated.

In classes III, IV, and V, none show over 15 per cent. of quartz in the norm.

As an example of the critical value of the silica content we may take the case of a foliated rock which falls in class I of the quantitative system and which shows evidence of sedimentary origin, either in its magnesia-lime ratio or its potash-soda ratio or both. If in the norm of this rock the quartz content exceeds 50 per cent. the evidence of its sedimentary origin is greatly strengthened. If the quartz exceeds 60 per cent. the evidence of sedimentary origin is even stronger.

It is to be noted that among the 30 pelite schist analyses classified in the table on p. 456, two are so quartzose as to fall in order 2 of class II where the ratio of quartz to feldspars in the norm is $>\frac{5}{3}$. There are

no representatives of this order among the igneous rocks of Washington's tables. Others among these schists show quartz in excess of the proportions given above as characteristic of igneous rocks.

EXAMPLES OF THE APPLICATION OF CHEMICAL CRITERIA

In conclusion, the application of the criteria which have been considered to certain type examples may aid in a fuller understanding of the principles involved.

The two gneisses described by Adams¹ from St. Jean de Matha and from Trembling Lake in Quebec show both a dominance of MgO over CaO and of K₂O over Na₂O. Both show more than 10 per cent. of corundum in the norm and thus fall in sub-class II of class II, characterized by only 4 doubtful analyses in Washington's tables. Adams' conclusion that they are of sedimentary origin would appear therefore to be well grounded.

| | 1 | 2 | 3 | 4 |
|--------------------------------------|----------|---------|--------|----------|
| SiO ₂ | 60.33% | 64.89% | 78.90% | 78.28% |
| Al ₂ O ₃ | 20.85 | 13.10 | 12.20 | 9.96 |
| Fe ₂ O ₃ | 3.59 | 4.99 | 2.30 | 1.85 |
| FeO..... | 4.47 | 0.99 | | 1.78 |
| MgO..... | 2.07 | 2.73 | 0.75 | 0.95 |
| CaO..... | 1.82 | 1.95 | 0.25 | 1.68 |
| Na ₂ O..... | 1.38 | 3.68 | 2.36 | 2.73 |
| K ₂ O..... | 2.84 | 5.46 | 0.24 | 1.35 |
| H ₂ O+..... | 2.78 | 1.60 | 1.90 | 0.83 |
| H ₂ O-..... | | 0.12 | | 0.12 |
| BaO..... | .... | .... | .... | .... |
| TiO ₂ | 1.41 | 0.98 | 0.50 | 0.70 |
| Total..... | 101.82%* | 100.49% | 99.40% | 100.44%† |

* Includes P₂O₅—0.28 per cent.

† Includes P₂O₅—0.11 per cent., MnO—0.08 per cent., and BaO—0.02 per cent.

No. 1. Gneiss from near Jenkintown Junction, Penn. Described as containing garnet, mica, feldspar, and magnetite. F. A. Genth, Jr., analyst, *Penn. Geol. Survey Report*, C⁶, p. 122.

No. 2. Muscovite-biotite gneiss from Pfelderstal, Tirol. Paul Seidel, *Beiträge zur Kenntnis der gesteinsbildenden Biotite*, Borna-Leipzig, p. 47, 1906.

No. 3. Muscovite gneiss from near Zell in the Fichtelgebirge, Bavaria. Rosenbusch, *Elemente der Gesteinslehre*, 2d ed., p. 488 (1901). For calculation of the norm the iron is apportioned as Fe₂O₃—1.32 per cent.—and FeO—0.98 per cent.—which is about the ratio of the two oxides in the average of the pelite schist analyses.

No. 4. Gneiss, Great Falls, near Washington, D.C., *Fifteenth Ann. Rept.*, U. S. Geol. Survey, p. 670 (1895).

¹ *American Journal of Science*, 3d series, Vol. L, p. 67 (1895).

A mica gneiss from near Jenkintown Junction, Pa., has the composition shown in Analysis No. 1 of the preceding table. When this rock is classified according to the quantitative system it is found to fall in class II, sub-class II. This sub-class is characterized by unusually high alumina content and has only four doubtful representatives in Washington's tables. The amount of corundum in the norm which is 12 per cent. is highly indicative of sedimentary origin. The presence of quartz in the norm to the extent of 33.18 per cent. is also somewhat suggestive of sedimentary origin. The double relationship of dominance of MgO over CaO and of K_2O over Na_2O is also shown. The sedimentary origin of this gneiss may therefore be regarded as beyond reasonable question.

Analysis No. 2 of the same table shows the composition of a muscovite-biotite gneiss from Pfelderstal in the Tirol, which is stated to be of sedimentary origin. The alumina content is of no critical significance in this case, no "excess" alumina being present. The silica content is also without critical value, since the rock falls in class II of the quantitative system and shows only 15.90 per cent. of quartz in the norm. The double dominance of MgO over CaO and of K_2O over Na_2O is however sufficient evidence to render a sedimentary origin highly probable.

Analysis No. 3 of the same table shows the composition of a muscovite gneiss stated to be of sedimentary origin, from the Fichtelgebirge in Bavaria. In this the potash does not dominate over the soda and although magnesia dominates over calcium yet the percentages of both are so small that this relation has less than the usual significance. A calculation of the position of this rock in the quantitative system places it in class I, sub-class I, order 2, and rang 4. Among the igneous rocks of Washington's tables there are no representatives of this rang, the percentage of lime being abnormally low in comparison with the alkalis. The attempt to classify this rock therefore serves to show at once its entire difference from any known igneous rocks. The alumina content is also suggestive of sedimentary origin, corundum being present in the norm to the extent of 7.55 per cent. The silica content is also significant, the 62.40 per cent. of quartz present in the norm being much in excess of that commonly found among the igneous rocks of class I. Sedimentary

origin is here indicated by three chemical criteria and may therefore be regarded as well established.

Analysis No. 4 shows the composition of a gneiss from the Great Falls of the Potomac near Washington, D. C. This rock was described by George H. Williams¹ and was believed by him to be of sedimentary origin. He says: ". . . the analysis . . . has no relation to any known igneous type, but agrees quite closely with certain siliceous sediments; so that, so far as the chemical evidence can be relied upon, we may safely regard the rock as of sedimentary origin."

The analysis of this rock shows neither a dominance of MgO over CaO nor of K₂O over Na₂O. There is also no excess of alumina above the amounts common in igneous rocks, less than 1 per cent. of corundum being present in the norm. The amount of quartz present in the norm is 52.14 per cent. This quartz percentage might be somewhat suggestive of sedimentary origin if supported by other criteria, but taken alone has little critical value for the reasons given on p. 468. This rock falls in class I, sub-class I, order 3, rang 2, and sub-rang 4, of the quantitative system, a subdivision numbering 16 other representatives in Washington's tables. In the opinion of the writer this analysis affords no valid evidence of sedimentary origin.

SUMMARY AND CONCLUSIONS

The chemical analysis, while in some cases of no critical value, is in many other cases a valid means of determining whether a foliated rock is of sedimentary or igneous origin.

The utility of chemical data depends upon the facts that the chemical characteristics of greatest critical value are developed in the belt of weathering during rock disintegration and decay, and that in very many of the igneous as well as the sedimentary rocks the chemical changes during the development of foliated structure are relatively slight.

In so far as igneous rocks have been affected by the processes of weathering either before or after the development in them of foliated structures, they tend to approach the sedimentary rocks in composition, and the criteria outlined in this paper become invalid.

¹ *Fifteenth Annual Report*, U. S. Geol. Survey, p. 670

For this reason only fresh foliated rocks should be used in chemical studies undertaken for the purpose of determining genesis.

In the case of foliates of *plutonic* igneous origin, weathering before the development of the foliated structure is believed to have affected so small a proportion of the rocks of this class that it is practically negligible for the purposes of this discussion.

Folates of *volcanic* origin may in many cases have been subject to weathering for considerable periods previous to the dynamic metamorphism which developed their parallel structures. In so far as extensive weathering has taken place, their differentiation from sediments on chemical grounds will be uncertain. It is probable, however, that in the majority of cases, weathering in rocks of this type has not been sufficient to obliterate their igneous characters.

Dominance of MgO over CaO is strongly indicative of sedimentary origin.

Dominance of K₂O over Na₂O is of lesser critical value, but is nevertheless suggestive of sedimentary origin.

The double relationship of dominance both of MgO over CaO and of K₂O over Na₂O affords very strong evidence of sedimentary origin.

The presence of any considerable excess of Al₂O₃ in the analysis over and above the 1:1 ratio necessary to satisfy the lime and alkalies, is also suggestive of sedimentary origin.

High silica content may be indicative of sedimentary origin when supported by other criteria. This criterion must, however, be used with caution, since silication probably takes place in the dynamic metamorphism of certain igneous rocks.

When three or all of the above relationships hold good, the evidence of sedimentary origin may be regarded as practically conclusive.

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